Journal of Process Control 24 (2014) 152–170

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Design of decoupling and tracking controllers for continuous-time transfer function matrices with multiple time delays

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ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form 31 October 2013
Accepted 2 November 2013
Available online 18 December 2013

Keywords:
Multiple time delays
Decoupling
Balanced model-reduction
Model reference tracking
Sliding mode control

ABSTRACT

This paper presents an extended adjoint decoupling method together with a reference model-based sliding mode tracking method, to design a decoupling and tracking controller for continuous-time transfer function matrices with multiple (integer/fractional) time delays in both denominators and numerators. First, for obtaining the diagonally decoupled subsystems, a decoupler is designed by utilizing the extended adjoint decoupling method. Then, by using sampled data from the unit-step response of the decoupled subsystems, the conventional balanced model-reduction method is carried out to obtain the approximated delay-free/single-delay continuous-time models for the decoupled subsystems with multiple time delays. For the integral of time multiplied by absolute error (ITAE) reference model tracking, a chain observer is designed to establish the virtual estimated states for the decoupled subsystems by utilizing the obtained approximated continuous-time models. At last, we develop a sliding mode tracking controller together with a disturbance observer (DOB), to achieve reference model tracking and disturbance rejection. Illustrative examples are given to demonstrate the effectiveness of the proposed method.

1. Introduction

Many industrial processes are represented by continuous-time transfer function matrices with a delay-free denominator and a multiple time-delay numerator matrix [1–3]. The different time delays and the multivariable nature of such processes often produce significant loop interactions which make the design of feedback controllers a difficult task, since the design approaches which are commonly used for single-input–single-output (SISO) processes cannot be directly extended to the multi-input–multi-output (MIMO) cases.

Many decoupling controller design methods for MIMO processes have been reported in the literature to reduce the interaction between different control loops, and take advantage of the well-developed SISO control design methodologies [2]. In general, the basic structures for continuous-time decoupling controller design can be roughly classified into: (i) ideal decoupling controller design [4–6], (ii) simplified decoupling controller design [4,7–9], (iii) inverted decoupling controller design [7,10–13], (iv) adjoint decoupling controller design [14] and (v) equivalent transfer function (ETF) based decoupling controller design [15]. Fig. 1 depicts the block diagram of the typical decoupling control structure for two-input–two-output (TITO) processes. In this figure K_i represent the performance controllers, D_{ij} the decoupler elements and G_{ij}, for $i, j = 1, 2$, the elements of the TITO process transfer function.

In ideal decoupling, the design goal is to make the multivariable process as simple as the diagonal elements in the process matrix $G(s) = [G_{ij}]$. However, the main difficulty of this method arises from its complexity and the realizability problem of the decoupler $D = [D_{ij}]$ [11]. In simplified decoupling, all terms of the decoupler D, commonly the diagonal ones, are set to unity. Thus, the design of the decoupler network is easier, but the complexity of the decoupled process is greater since it consists of the determinant of $G(s) = [G_{ij}]$. In the inverted decoupling method, an additional controller is added to simplify the structure of the decoupled open-loop system in the simplified decoupling procedure. As a result, the final decoupling controller, which involves an inverted term, can be represented as a forward controller. Instead of using the inverse of the time-delay transfer function matrix to design the decoupler, the adjoint decoupling method utilizes the adjoint of the numerator matrix to construct the decoupling controllers. Then, classical frequency design methods can be chosen such

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0959-1524/$ – see front matter
http://dx.doi.org/10.1016/j.jprocont.2013.11.002

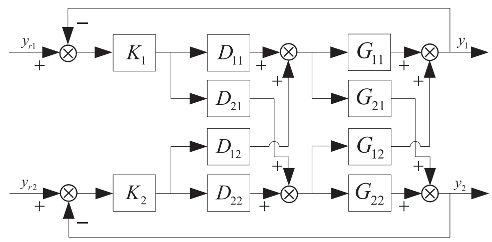

Fig. 1. Block diagram of the decoupling control structure for TITO processes.

that the decouplers are practically realizable, and the decoupled process can be designed to satisfy some desirable control specifications such as the damping ratio, the undamped natural angular frequency, etc. In ETF based decoupling, the decoupler is designed indirectly by utilizing the closed-loop equivalent transfer function together with a properly specified diagonal transfer function matrix. Thus, the ETF based method is simple and easy to be applied by field control engineers [15].

With the development of the decoupling control theory, many design methodologies have been proposed for TITO processes with a delay-free denominator and a multiple time-delay numerator [12]. This is due to the fact that (i) many real multivariable processes are TITO, or (ii) a complex process can be decomposed into special TITO processes. On the other hand, not much research work has been carried out for the case of continuous-time transfer function matrices with multiple (integer/fractional) time delays in both denominators and numerators [16]; only few published works consider the state delays in the transfer function models using the input–output design method [17]. To deal with such a multivariable process with general time delays, the conventional approach is to determine an approximated delay-free transfer function matrix by means of Pade approximants [1,2]. Nevertheless, the stability and system performance of the approximated model cannot be guaranteed [18–20].

In this paper we develop a decoupling method, which extends the adjoint decoupling method from continuous-time delay-free transfer function matrices [14] to MIMO continuous-time transfer function matrices with multiple (integer/fractional) time delays in both denominators and numerators. In addition, to take advantage of the valuable properties of the sliding mode control [21], such as low sensitivity to external disturbances and robustness with respect to plant parameter uncertainties and variations, we propose a reference model-based sliding mode tracker for the afore-mentioned multiple time-delay transfer function matrix. For simplicity in presentation, we focus on TITO processes. According to the proposed extended adjoint decoupling method, two decouplers are first constructed to obtain the decoupled multiple time-delay subsystems. Then, using sampled data from the unit-step response of the decoupled subsystems, the conventional balanced model-reduction method is carried out to obtain approximated discrete-time/continuous-time models for the afore-mentioned decoupled subsystems which contain multiple time delays. In order to track the outputs of the ITAE (integral of time multiplied by absolute error [22]) optimal reference model plus input/output dead time, a chain observer [23,24] is designed to estimate the states of the obtained approximated state-space model, i.e. to establish the virtual estimated states for the decoupled subsystems. As a result, the sliding mode control design method, developed for systems in the time domain, can be applied in the frequency domain to achieve the tracking of the reference model for continuous-time transfer function matrices with multiple (integer/fractional) time delays in both denominators and numerators.

The paper is organized as follows. In Section 2, the extended adjoint decoupling method is studied for a continuous-time transfer function matrix with general time delays. In Section 3, approximated discrete-time/continuous-time models for the diagonally decoupled subsystems are determined by means of the balanced realization and model-reduction methods. In Section 4, a chain observer is designed to compensate the output delay of the approximated continuous-time state-space model, and construct the virtual estimated states for the decoupled subsystems. Then, a sliding mode controller is proposed to track the output of the ITAE optimal reference model plus input/output dead time by using the virtual estimated states. For robust performance, a disturbance observer is designed in Section 5 to obtain internal/external disturbance rejection capabilities. Two illustrative examples are presented in Section 6, and conclusions are given in Section 7.

2. Decoupling method

For simplicity in presentation, we consider a stable TITO process with multiple time delays given as

$$G(s, e^{-(\cdot)s}) = [G_{ij}(s, e^{-(\cdot)s})]_{2\times 2} \tag{1}$$

where $G_{ij}(s, e^{-(\cdot)s}) = N_{ij}(s, e^{-(\cdot)s})/D_{ij}(s, e^{-(\cdot)s})$, for $i, j = 1, 2$, represent the transfer function of the (i, j)th subsystem, where $N_{ij}(s, e^{-(\cdot)s})$ and $D_{ij}(s, e^{-(\cdot)s})$ are, respectively, the numerator and denominator of such transfer function, with $e^{-(\cdot)s}$ in $N_{ij}(s, e^{-(\cdot)s})$ and $D_{ij}(s, e^{-(\cdot)s})$ representing the delay term, possibly consisting of delay combinations. Also, we write the stable transfer function matrix in (1) as

$$G(s, e^{-(\cdot)s}) = \frac{\Phi(s, e^{-(\cdot)s})e^{-\tau s}}{d(s, e^{-(\cdot)s})} \tag{2}$$

where $d(s, e^{-(\cdot)s})$ is the stable least common denominator of the transfer function matrix $G(s, e^{-(\cdot)s})$, $\Phi(s, e^{-(\cdot)s}) = \begin{bmatrix} \phi_{11}(s, e^{-(\cdot)s}) & \phi_{12}(s, e^{-(\cdot)s}) \\ \phi_{21}(s, e^{-(\cdot)s}) & \phi_{22}(s, e^{-(\cdot)s}) \end{bmatrix}$ is the numerator matrix and $e^{-\tau s}$ is the smallest common delay term in the multiple time-delay numerator matrix in $G(s, e^{-(\cdot)s})$.